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LORAN C Stability Integrity Assurance

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Thomas Wisser

June 1989

DOT/FAA/CT-TN88/13

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16. Abstract

This report describes a program to determine if an operational integrity check is necessary before beginning a Loran C nonprecision approach. Simulation testing and a questionnaire distributed to Loran C receiver manufacturers were used to determine if present state-of-the-art receivers could reliably acquire the Loran C signal. The questionnaire was designed to solicit from manufacturers the probability of reliable acquisition for state-of-the-art receivers and if improvements are possible. Flight tests were also conducted to gather preliminary information related to employing Loran C operational integrity checks prior to initiating a nonprecision approach.

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EXECUTIVE SUMMARY

This report describes a program to determine if an operational integrity check (OIC) is necessary and to develop procedures for conducting an OIC. Simulation testing and a questionnaire distributed to Loran C manufacturers were used to determine if present state-of-the-art receivers could reliably acquire the Loran C signal.

The questionnaire was designed to solicit from manufacturers the probability of reliable acquisition for state-of-the-art receivers and if improvements are possible. Flight tests were conducted to develop OIC techniques and to determine the feasibility of an OIC.

The simulation tests demonstrate that present state-of-the art receivers can acquire on the wrong cycle under certain conditions. If the signal-in-space criteria (i.e., signal-to-noise ratio (SNR) and field strength) are increased, the likelyhood of acquiring on the proper cycle is improved. Some of the questionnaire answers support this conclusion.

Manufacturers should be required to furnish statistical information with respect to cycle acquisition and minimal signal conditions to receive Federal Aviation Administration (FAA) approval. The receiver simulation tests presented in this document were used to support the FAA position with respect to signal acquisition and track integrity requirements in Technical Standard Order (TSO)-C-60B published May 1988.

INTRODUCTION

OBJECTIVE.

The objective of this program is to determine if an operational integrity check (OIC) is necessary before beginning a Loran C nonprecision approach and to develop procedures for conducting an operational integrity check.

BACKGROUND.

Loran C is approved as a supplemental air navigation system. The Federal Aviation Administration (FAA) has made a committment to install signal monitors necessary for Loran C nonprecision approaches. These monitors will be installed and become operational in 1989.

Loran C expansion will be supported by installing four Loran C transmitters to fill the mid-continent gap. Loran C nonprecision approaches will be supported by installing 196 monitors to provide an integrity check of the local Loran C signal in space and to provide local area bias corrections on a routine basis for the airborne receivers.

Loran C Minimum Operational Performance Standards (MOPS) (Related Documentation 1) have been developed through a joint effort of users, manufacturers, the FAA, and the Radio Technical Commission for Aeronautics (RTCA). The intent of the MOPS committee was to agree on a set of standards that all participants could live with and that would not compromise safety issues.

The safety issue was addressed in the MOPS by requiring the receivers to detect blink within 10 seconds and loss of signal within 15 seconds, down to a signal-to-noise ratio (SNR) of -6 decibels (dB) in the approach mode. The blink and loss of signal detection criteria were increased to 60 and 30 seconds, respectively, down to -10 dB SNR for the en route and terminal mode. At present, the United States Coast Guard (USCG) detects out of tolerance parameters and manually asserts blink. The FAA has requested the USCG to automate the assertion of blink. The FAA has recognized deficiencies in the integrity requirements of the MOPS as a result of some of the data presented in this report and has included requirements intended to satisfy the integrity deficiencies in the Technical Standard Order (TSO)-C-60B.

The FAA had addressed the safety issue by initially restricting approaches in the early implementation program to geographical areas meeting good signal in space criteria, i.e., SNR shall be equal to or greater than 0 dB, envelope-to-cycle difference (ECD) shall not exceed ± 2.4 microseconds, and geometric dilution of precision (GDOP) shall not exceed 3000 feet/microsecond. The approaches were also overlaid over another navigation aid (NAVAID) approach and a copilot was required to monitor the Loran C approach with respect to the other NAVAID. There is a concern over the ability of a Loran C receiver to reliably acquire and track the Loran C signal on the proper cycle. If Loran C is to gain wide acceptance and approval in the NAS, this issue must be resolved in the receiver design and by limiting operation to areas where wrong cycle acquisition is improbable. The MOPS addressed this issue by requiring receivers to detect or correct a cycle slip with 90 percent probability within 10 minutes in the en route and terminal mode and within 3 minutes in the approach mode. The MOPS did not specify the probability associated with the approach mode. However, the test section of the MOPS requires the receiver under test to detect a cycle slip in 20 out of 20 test cycles. The MOPS required the receivers to detect loss of signal within 30 seconds for en route and 15 seconds for approaches. In addition, the MOPS required the receivers to properly acquire and track with an ECD of 0 to -2.4 microseconds at SNR's from -6 to -16 dB and ECD's of -2.4 to +3.0 microseconds at SNR's above -6 dB. An FAA/NASAO Working Group was established to revise this criteria.

RELATED DOCUMENTATION.

1. Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using Loran C Inputs, RTCA/DO-194, November 17, 1986.

2. Technical Standard Order, TSO-C-60B, May 1988.

3. Loran C Monitor Analysis, Critical Design Review-2 Data Package Report, Report NL-21, Martin Marietta, ATC Division, May 1986.

4. Till, Robert D., Helicopter Global Positioning System Navigation with the Magnovox Z-Set, DOT/FAA/CT/TN83/03, February 1983.

5. United States Standard Flight Inspection Manual, OAP 8200.1, April 22, 1983.

EQUIPMENT AND DATA COLLECTION

SIMULATOR.

The simulator used to test state-of-the-art receivers was an ANI-2500 Loran C simulator described in appendix A.

QUESTIONNAIRE.

The questionnaire distributed to Loran C receiver manufacturers is presented in appendix B.

COMMISSIONED NAVAIDS.

Methods were evaluated using commissioned NAVAIDS in the event an operational integrity check is required. The commissioned NAVAIDS evaluated were a non-directional beacon (NDB), a very high frequency omnidirectional (VOR), and a marker beacon. The VOR is the standard short range air NAVAID in use by the United States. The VOR system, comprised of the ground transmitting equipment and airborne reciever, provides visual indication of the course between the ground and airborne antenna on any azimuth selected by the pilot.

The NDB, also known as a low or medium frequency homing beacon, transmits non-directional signals whereby the pilot can determine his bearing and "home" on the station. When a low frequency non-directional beacon is used in conjunction with the instrument landing system (ILS), it is called a compass locator.

The marker beacon is a very high frequency (VHF) radio transmitter which propagates an elliptically shaped (fan) vertical radiation pattern. The pattern is composed of a major and minor axis. The major axis is defined as the largest diameter of the ellipse, while the minor axis is the shorter diameter. Functionally, marker beacons provide an aural and visual indication of station passage in association with facilities providing course guidance, such as an ILS.

AIRBORNE DATA COLLECTION SYSTEM.

Flight test operations were conducted in an FAA Convair 580 aircraft (N-91). Figure 1 is a functional diagram of the test instrumentation which was employed for all OIC data collection. A Norden militarized PDP 11/34 computer and 9-track tape recorder recorded Loran C data from two ANI 7000 Loran C receivers. Both receivers were area calibrated and operated in the approach, dedicated triad mode to insure basic single chain, three-station operation for all flight test phases. All data related to measurements of commissioned navigation aid parameters, such as cone of silence, beam width, and radial intersection accuracy, were collected manually or by strip chart recorder using the appropriate system and indicators located in the aircraft flight deck and the flight inspection console. The extended area instrumentation radar (EAIR) and Nike-Hercules radar tracking facililty provided timing and served as position reference during the flight tests where coverage was available. These facilities generated plots and position reference tapes for data reduction purposes. In addition, global positioning system (GPS) receivers installed in the aircraft were used for a position reference system when the GPS satellite window coincided with the flight tests.

TEST PROCEDURES

LABORATORY TESTS.

Simulation tests were conducted using the ANI-2500 Loran C simulator described in appendix A. The tests were designed to determine the minimum SNR where state-of-the-art Loran C receivers operating in the approach mode can properly acquire Loran C signals with a high degree of probability. Typical test values are shown in table 1. The field strength was held constant; the noise level was varied to obtain the desired SNR. The acquisition test was repeated 100 times to provide meaningful statistics.

Gaussian noise scaled to atmospheric with an 8 dB scaler was used as a noise test input. Gaussian noise was selected because it is the easiest to describe and reproduce. The station geometry at the FAA Technical Center was selected as a test location because of the ideal Loran C GDOP. The ECD of the master was selected as +3.0 microseconds and the secondaries were set at -2.4 microseconds.

A failure was declared when the receiver did not acquire all three stations properly within 500 seconds or the set failed to annunciate a wrong cycle acquisition.

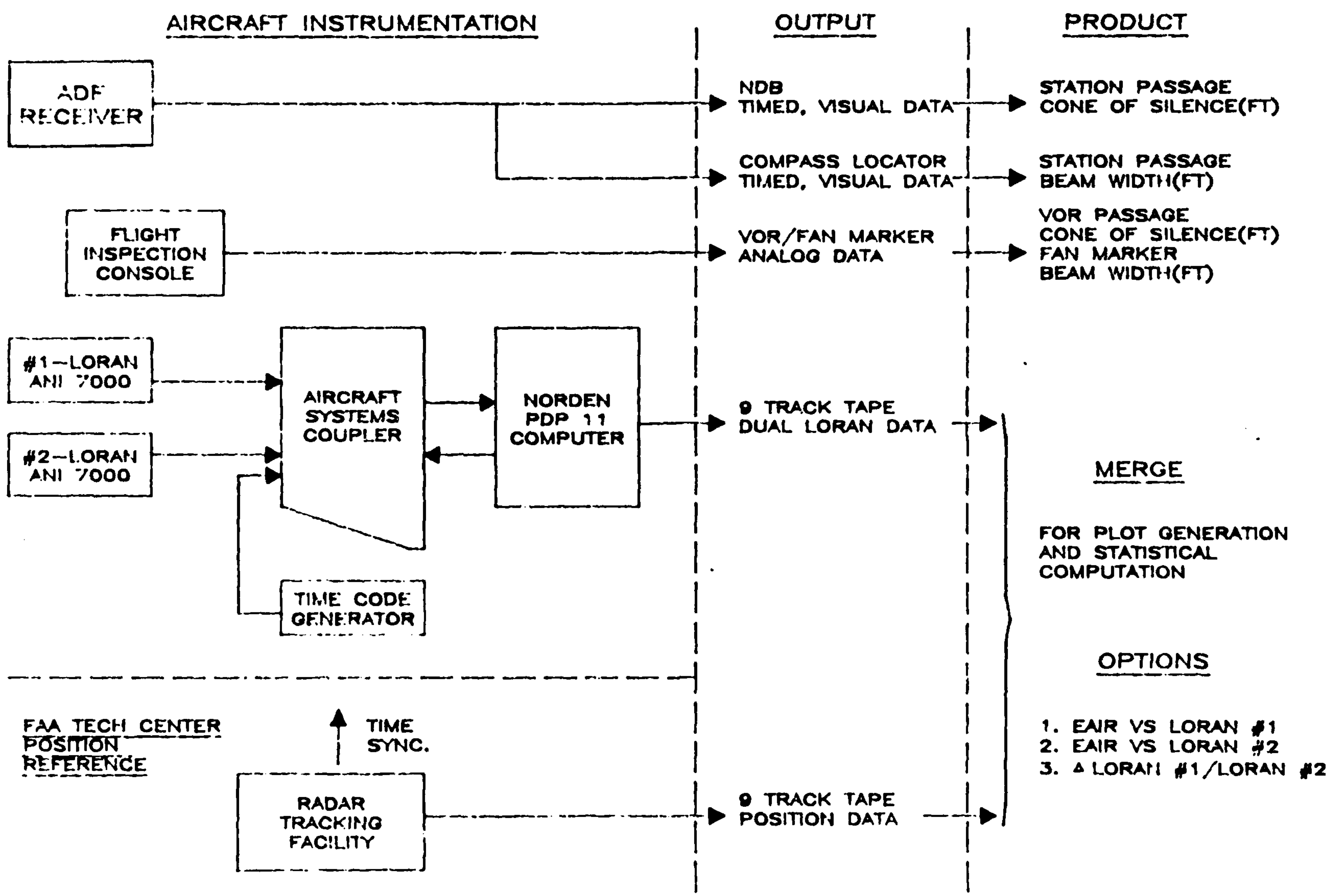

FIGURE 1. AIRBORNE DATA COLLECTION SYSTEM

TABLE 1. LORAN C SIMULATOR TESTS

Chain 9960 GRI

Triad	Test Location
(M) Master, Seneca, NY	Atlantic City, NJ
(X) Secondary, Nantucket, MA	Latitude 39° 27'N
(Y) Secondary, Carolina Beach, NC	Longitude 74° 34'W
	GDOP 938 ft/microsecond

Station	Field Strength dB/microvolt/meter	ECD microseconds	Noise dB/microvolt/meter
M	110	+3.0	varied
X	50	-2.4	varied
Y	50	-2.4	varied

QUESTIONNAIRE.

The questionnaire in appendix B was distributed to several receiver manufacturers. The results of the questionnaire were used to reinforce or validate the findings of the simulation tests to determine if the integrity can be improved in the next generation receivers.

FLIGHT TESTS.

Approximately 10 hours of tests were conducted in an FAA (CV-580) aircraft. Testing was divided into two phases as follows:

PHASE 1. A series of over-flights of several commissioned navigation facilities located in the vicinity of the Millville Airport and the Atlantic City International Airport were made in order to measure the width of signal reception or signal loss characteristics of typical commissioned NAVAIDS. Repeat flights at altitudes appropriate to terminal area operations aided in establishing the propagation pattern with relation to height above the facility. The NAVAIDS tested were incorporated as intermediate, initial, and final fixes for published approaches used in testing. NAVAIDS incorporated in flights included Rainbow nondirectional beacon (NDB), Cedar Lake and Atlantic City very high frequency omnidirectional range/tactical air navigation (VORTAC's), and the compass locator at the Atlantic City runway 13 outer marker. This phase of flight testing terminated with an NDB approach to the Atlantic City International Airport using NAVAIDS and procedures described in published approach plates. Phase 1 flight tests also served to check out Loran C area calibration, pseudo cycle slip technique (weakest signal time difference adjusted +10 microseconds), and approach routing employed during phase 2 flight testing.

PHASE 2. A minimum of four published approaches, including holding patterns, were flown at Millville, Atlantic City, and Wildwood/Cape May. The two ANI 7000 Loran C receivers were calibrated and programmed identically for local approach mode operations. Additionally, Loran C receiver number 2 had its weakest received signal station (TD) adjusted +10.0 microseconds. With this configuration, when Loran C receiver number 1 was remoted to the flight course deviation indicator (CDI), the aircraft should be on course, and when Loran C receiver number 2 was remoted to the flight CDI, the needle operated with a position error similar to that caused by an undetected cycle slip. Approaches were made with the pilot-in-command flying Loran C only for guidance. The pilot did not know if the guidance being remoted to the cockpit had, in fact, an error introduced. It was up to the pilot to determine if the Loran C receiver had a cycle slip or not (two subject pilots were used).

Post-flight data analysis provided accurate measurements of station passage transmitted signal characteristics at several typical NAVAIDS, and, as a limited demonstration, indicated whether such station passages were usable for an OIC in the Atlantic City Loran C environment. Station passage measurements could also be applied to other areas with the same type of NAVAIDS.

TEST RESULTS AND DATA ANALYSIS

SIMULATOR TESTS.

The results of the simulator tests are presented in table 2. (Note the MOPS criteria is stated with respect to atmospheric noise.) Gaussian noise was used in the tests. Atmospheric noise equals Gaussian noise plus 8 dB. Three different models of state-of-the-art receivers were tested (ANI 7000 and II Morrow models 612A and 612B). Using signal strengths less than 40 decibels per microvolt per meter (dB/μV/m) resulted in either failure to acquire on time or wrong cycle acquisition. At signal strengths of 50 dB/μV/m, the noise was lowered until no cycle slips occurred in the II Morrow receiver at approximately 0 dB SNR.

The ANI 7000 receiver would not acquire when using the Atlantic City coordinates at low SNR values. The ANI receiver uses predicted signal conditions to determine if the actual signals at a location are reasonable. The receiver determined the SNR values were unrealistic. Therefore, the location described in the note of table 2 was selected since the SNR in that area is normally low. However, at this location using the MWY triad, the ANI receiver experienced both cycle slips and time failures (June 18 and 24, 1987). The reason for the acquisition failures was that the the GDOP for that triad was high, 4120 feet/microsecond. The MWX triad was selected since it had a much lower GDOP of 2872 feet/microsecond, and tested with no cycle slips (June 25, 1987).

Tests conducted on June 25 and June 29, 1987, are used as the basis for the following discussion. Both the ANI 7000 and the II Morrow 612A Loran C receivers were tested with identical simulator settings 100 times each. The results of these tests indicate that there were two time failures out of 100 tests for the ANI model and three wrong cycle acquisitions out of 100 tests for the II Morrow receiver.

The time failures are not a critical factor since the receiver cannot be used for navigation until the set acquires. The cycle slips are of great concern. The II Morrow receiver would actually acquire with no warnings or flags and "assume" the coordinates displayed were correct. About 15 minutes later the

TABLE 2. RESULTS OF SIMULATION TESTS FOR LORAN RECEIVER ACQUISITION

Date	Mfr	Model	S/N	M	W	X	Y	GN	M	W	X	Y	Try	C	T
12/9/86	II Morrow	612A	22421	110		30	30	32	+3.0		-2.4	-2.4	20	1	1
12/9/86	II Morrow	612A	22421	110		30	30	22	+3.0		-2.4	-2.4	15	1	0
?	II Morrow	612A	22421	40	40	40		42	-2.4	-2.4	-2.4		10	3	2
?	II Morrow	612A	22421	40	40	40		32	-2.4	-2.4	-2.4		13	2	3
?	II Morrow	612A	22421	110		30	30	40	+3.0		-2.4	-2.4	17	0	0
?	II Morrow	612A	22421	110		30	30	30	+3.0		-2.4	-2.4	5	5	0
?	II Morrow	612A	22421	110		30	30	25	+3.0		-2.4	-2.4	6	1	0
?	II Morrow	612A	22421	110		30	30	30	+3.0		-2.4	-2.4	9	0	0
?	II Morrow	612A	22421	110		30	30	32	+3.0		-2.4	-2.4	25	3	4
1/07/87	II Morrow	612A	22421	110		30	30	22	+3.0		-2.4	-2.4	30	1	0
1/07/87	II Morrow	612A	25721	110		30	30	32	+3.0		-2.4	-2.4	30	8	0
1/07/87	II Morrow	612A	25721	110		50	50	52	+3.0		-2.0	-2.0	100	3	0
1/13/87	II Morrow	612A	25721	50		50	50	52	-2.0		-2.0	-2.0	30	1	0
1/13/87	II Morrow	612A	25721	110		50	50	50	+3.0		-2.4	-2.4	60	2	1
1/22/87	II Morrow	612A	25721	110		50	50	48	+3.0		-2.4	-2.4	70	2	0
1/23/87	II Morrow	612A	25721	110		50	50	60	+3.0		-2.4	-2.4	16	0	0
1/28/87	II Morrow	612A	25721	110		50	50	40	+3.0		-2.4	-2.4	100	0	0
2/02/87	II Morrow	612A	25721	110		50	50	42	+3.0		-2.4	-2.4	100	0	0
2/11/87	II Morrow	612A	25721	110		50	50	46	+3.0		-2.4	-2.4	59	1	0
3/31/87	II Morrow	612A	25721	110		50	50	52	+3.0		-2.4	-2.4	100	1	3
6/18/87	ANI	7000	1345	45	110		45	47	+1.4	+2.5		+0.7	105	1	4
6/24/87	ANI	7000	1345	50	110		50	52	-2.4	+3.0		-2.4	14	1	1
6/25/87	ANI	7000	1345	40	110	40		42	-2.4	+3.0	-2.4		100	0	2
6/29/87	II Morrow	612A	25721	40	110	40		42	-2.4	+3.0	-2.4		100	3	0
7/01/87	II Morrow	614R	15539	40	110	40		42	-2.4	+3.0	-2.4		21	1	0

Mfr: manufacturer
S/N: serial number
GN: gaussian noise, dB/microvolt/meter
Try: number of trials
C: number of cycle slips
T: number of time failures
M,W,X,Y - Loran C station identification

Note: From 6/18/87 and later, the latitude used in the simulation tests was N46 53.0' and longitude W119 44.0' which is located in the 9940 GRI. Originally the MWY triad was used with W being the strongest signal. That triad had a poor GDOP so triad MWX was used starting on 6/25/87.

receiver did determine a cycle slip had occurred and illuminate the warning annunciator. About 10 minutes after this, the receiver acquired the correct cycle. Ninety-seven correct acquisitions out of 100 does not provide a satisfactory probability and confidence level to certify a Loran C receiver for flying instrument flight rules (IFR) en route, in terminal areas, or for nonprecision approach.

According to the MOPS, receivers must detect or correct a cycle slip with 90 percent probability within 10 minutes in 10 trials in the en route and terminal mode and within 3 minutes and 20 out of 20 tests in the approach mode.

QUESTIONNAIRE RESPONSES.

The responses from the questionnaire (appendix B) are summarized in table 3. Only three manufacturers replied and their complete replies are listed in appendix D, excluding any reference to the names of the manufacturer or model numbers.

The manufacturers who replied are of the opinion that it is possible to design an economically feasible receiver that will acquire and track on the proper cycle with nearly 100 percent probability--under certain conditions. Each manufacturer feels they have resolved the cycle acquisition issue in their receivers. FAA test results show that the state-of-the-art receivers tested did not satisfy the cycle slip issue using the MOPS minimum signal-in-space criteria.

FLIGHT TESTS.

PHASE 1. Flight tests were accomplished using an FAA Convair 580 aircraft equipped with a flight inspection console. The console consisted of one VOR receiver, 75 MHz marker beacon receiver, analog data recorder, and other related subunits. Bearing position reference for all flight testing was obtained from the EAIR. VOR site parameters were measured with the flight inspection system and recorded on a strip chart recorder. Data collected included VOR course deviation, field strength, automatic gain control (AGC), and modulation levels.

Methodology used for overflying the Rainbow NDB at the Millville Airport consisted of four runs at altitudes of 1000, 2000, 3000, and 4000 feet. The needle swing or course reversal was timed with the use of a stopwatch using the standard formula:

$$\text{Width (ft)} = \frac{\text{TAS X TAV}}{0.592}$$

whereas, TAS is true airspeed in knots, TAV is time average in seconds, and 0.592 is a constant. The respective widths of the NDB were 1295, 1867, 2046, and 2298 feet.

Indications of the automatic direction finder (ADF) needle and aural indentification are the primary means of checking accuracy over the station. Incorrect bearing indication of the ADF needle may be caused by radio or terrain interference and by weather phenomenon. The principle manifestations of interference from another radio station are "hunting," erroneous bearing, or distortation. Since coverage of the beacon will be affected by weather, flights

TABLE 3. SUMMARY OF REPLIES TO QUESTIONNAIRE FROM THREE MANUFACTURERS

1. Is it possible to design a receiver that will acquire and track on the proper cycle with nearly 100% probability?

A: 95% if greater than -10 dB SNR
97% if greater than -6 dB SNR
99.5% is obtainable
100% not obtainable

B: Nearly 100% if range is limited to 600 nautical miles

C: 99.9% with 60% confidence for 1000 out of 1000 tests

2. If the answer to question 1 is yes, is it economical to manufacture a receiver that will nearly always acquire and track on the proper cycle?

A: Yes

B: Same reply as in question 1

C: Yes

3. In your opinion, have you resolved the cycle slip issue with proprietary software or hardware?

A: Yes, by tracking up to 10 stations

B: Yes, with limits in reply to question 1

C: Yes

4. If operation is restricted to geographical areas with good signal-in-space coverage, i.e., SNR and ECD above some minimum value, to what probability can you guarantee proper cycle acquisition and track? Specify the SNR, ECD, and other criteria to meet that probability?

A: SNR -10 dB and ECD +3 μs and at least 3 secondaries or more than 1 chain

B: SNR -10 dB and ECD +2.5 μs

C: SNR -2 dB and ECD +2.4 to -2.4 μs and signal 50 dB or
0 dB and ECD +2.4 to -2.4 μs and signal 40 dB or
-6 dB and ECD +1.0 to -3.5 μs and signal 40 dB

TABLE 3. SUMMARY OF REPLIES TO QUESTIONNAIRE FROM THREE MANUFACTURERS (CONTINUED)

5. What improvements, if any, would you recommend to the MOPS or a TSO to increase confidence in proper cycle acquisition of track?

A: Use of 2 chains

B: With new RTCA DO-194 conditions

C: Antenna simulator is not a good test. Need to provide calibration for simulator.

6. What undetectable receiver failure modes, if any, could cause wrong cycle acquisition or detection?

A: If envelope detection circuit or filters are detuned, this could cause ECD errors which could cause cycle errors.

B: Detuning the RF circuits or poorly located notch filters could cause pulse distortion which could cause a change in the ECD which could cause cycle slip. Pulse distortion may occur in the mountains but can be determined in surveying for approach certification.

C: Our receiver meets safety analysis.

7. In your opinion, is an OIC necessary?

A: On rare occasions when a set must be reinitialized in flight

B: No

C: No, suggest reasonableness check

8. Can a GCP be used in place of an OIC?

A: Not necessary

B: Not necessary

C: Same reply as question 7

9. Do you have any other comments or suggestions to resolve the cycle slip issue?

A: Use multiple chains and stations

B: Cycle slips are not a problem in most areas

C: Proprietary information

over the station should only be attempted in good conditions. For this reason alone, an NDB is not recommended as an integrity check point for Loran accuracy.

The width of the outer marker on the ILS approach to runway 13 at the Atlantic City International Airport was recorded and measured by using standard flight inspection methods. The pilot flew a standard ILS approach. Using the formula described in the previous paragraph, the width of the minor axis was found to be 1952 feet. Optimum limits for the minor axis is 2000 feet $\pm$650 feet not to exceed 4000 feet. Limits for the major axis is any distance not to exceed the respective minor axis tolerance.

Several radial overflights of the Cedar Lake VOR (VCN) and the Atlantic City VOR (ACY) were flown at an altitude of 2000 feet. The 100° and 190° radials were flown to and from the station to measure the "cone-of-silence," (the area of no signal). An indication of the cone of silence is that the OBS flag appears, the "to-from" indicator reverses, and the azimuth bearing needle reaches full scale. Using the standard formula, the width of the cone-of-silence of VCN was 1445 feet and ACY was 1800 feet. As altitude increases, so does the width increase. The pilot in command chose 2000 feet as an altitude he would use if using a VOR as an integrity check point.

PHASE 2. The objective of the second series of flights was to ascertain whether or not a pilot could, in fact, determine if the Loran information is accurate or if a cycle slip has occured.

Two identical ANI 7000 Loran receivers were installed on the aircraft, and a CDI was remoted to the cockpit. The pilot was instructed to fly Loran only and monitor distance to the NAVAID and needle variations.

Both receivers were turned on at the same time and acquired within 1 minute of each other. For test purposes, the number 2 receiver was programmed with a 10μs error to simulate a cycle slip. The receivers were in dedicated triad (9960, M,X,Y) and area calibration. Point number 10 on the ACY ramp was used as a calibration point (39°27.00'N, 074°33.90'W). Five approaches were flown to ILS runway 13 at the Atlantic City International Airport. All approaches commenced by overflying the Cedar Lake VOR on the 100° radial to intercept the localizer (see figure 2). Two approaches were flown with the pilot flying normal Loran guidance to threshold. Three approaches were flown using the erroneous Loran guidance from the number 2 Loran receiver. In all cases, the pilot overflew the VOR and correctly determined the integrity of the Loran. Crosstrack error was 1 nautical mile (nmi) to the right. When over the station, the pilot observed the Loran CDI and noted that the needle was not centered and was, in fact, four dots to the left (1 dot equals 0.25 nmi). It was enough, in his opinion, to question the accuracy of the Loran. The approach was continued (see figure 3) flying the needle, and at threshold the aircraft was 300 feet to the right. Subsequent flights were repeatable.

Millville Airport and Cape May Airport were chosen for additional approaches since they are in the same area for calibration purposes. Waypoints were stored for automatic sequencing and the receivers were operating in the approach mode.

Four approaches were flown at Millville to runway 14/32 using Loran only (see figure 4). Runs 2 and 3 were flown with the subject pilot flying Loran number 2 as guidance. The crosstrack error was 0.4 nmi and along-track error was 1.2 nmi

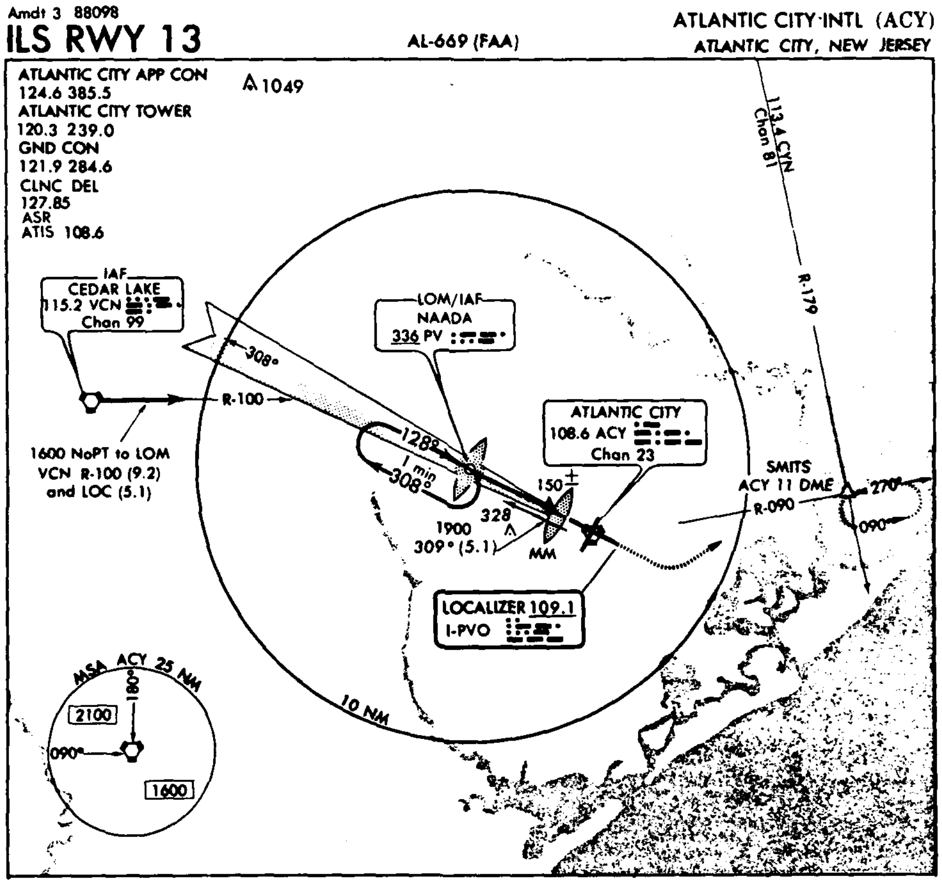

FIGURE 2. ATLANTIC CITY AIRPORT APPROACH PLATE

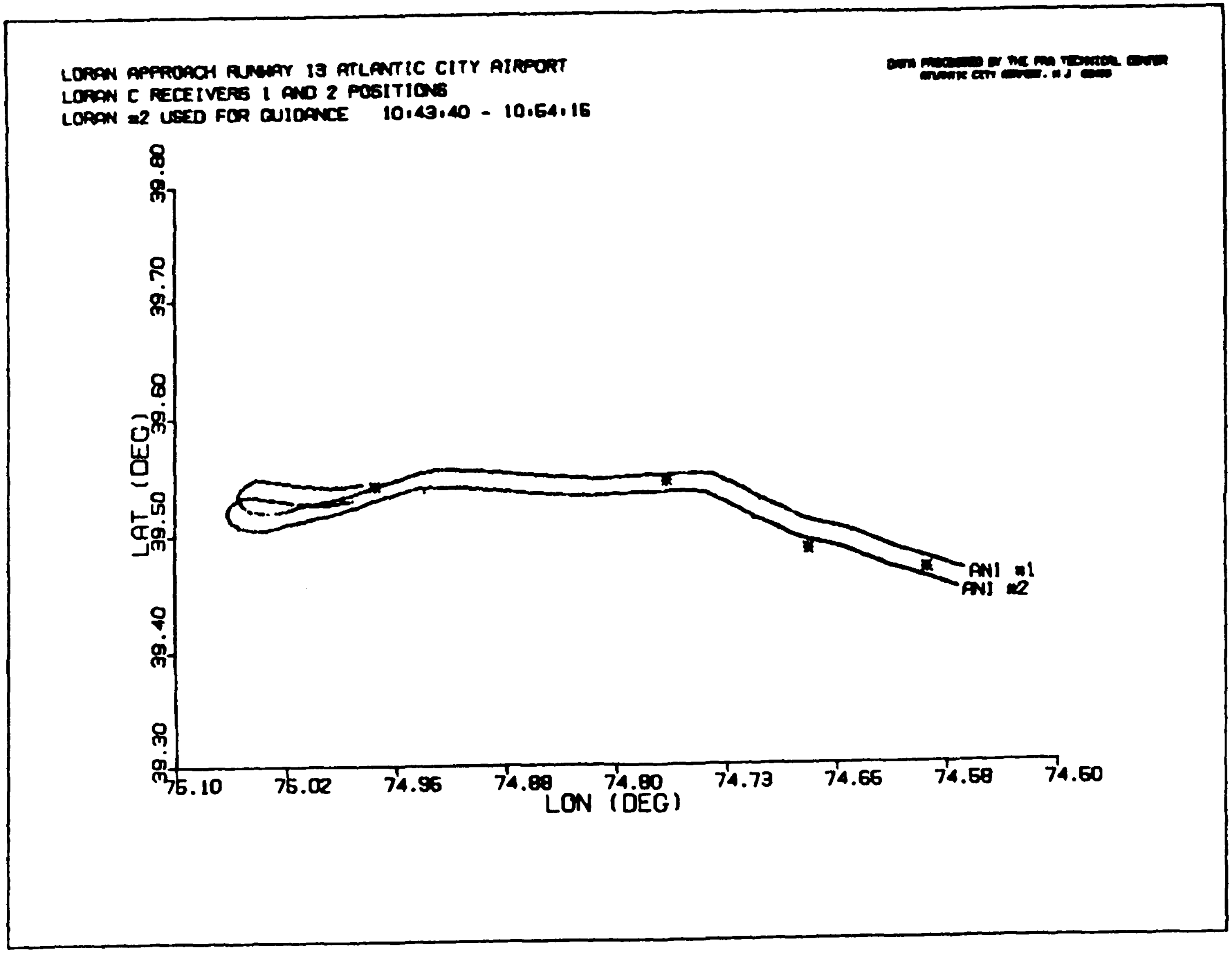

FIGURE 3. APPROACHES, ATLANTIC CITY INTERNATIONAL AIRPORT

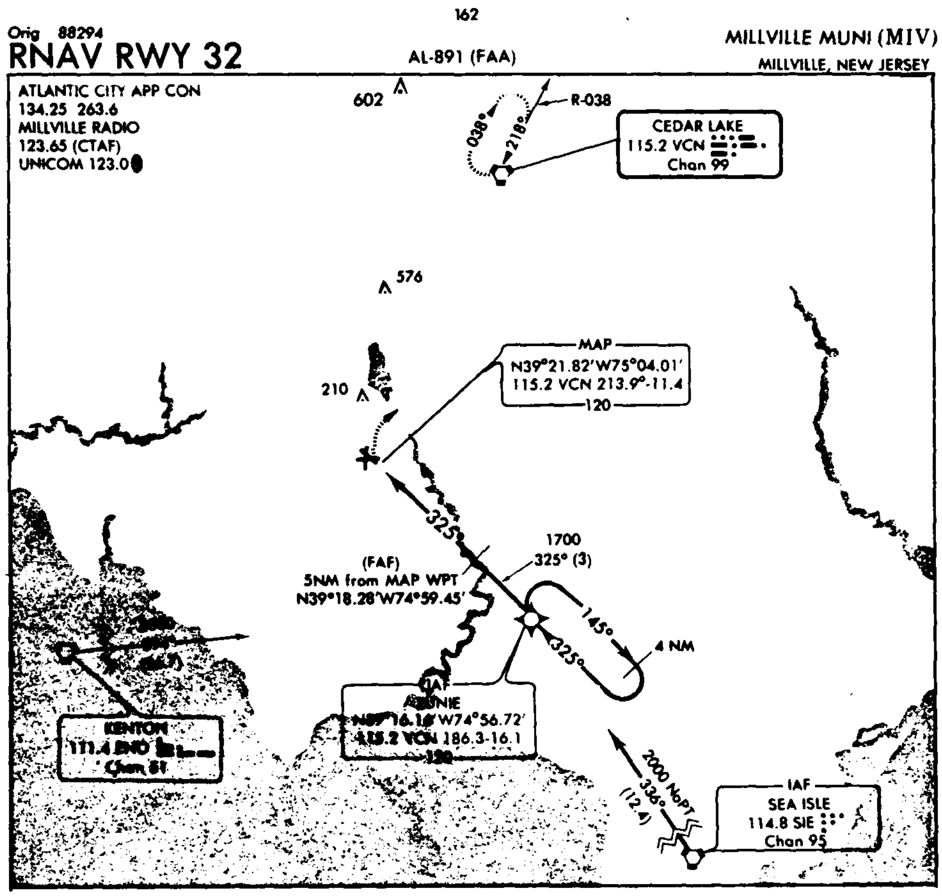

FIGURE 4. MILLVILLE AIRPORT APPROACH PLATE

(see figure 5). The subject pilot could not determine with assurance whether or not the Loran was correct when overflying the Cedar Lake VOR using only the CDI information. At the Cedar Lake VOR, the Loran receiver along-track error was 1.2 nmi when the VOR to/from flag indicated station passage. Visual siting also indicated the aircraft had overflown the VOR. Therefore, Loran distance to go must be monitored.

At Cape May Airport, the Sea Isle VOR (SIE) and CAGYS intersection were used as checkpoints (see figure 6). Again, the along-track error was 1 nmi and the crosstrack error was 0.5 nmi. With this situation, the pilot could not determine if the Loran was in error using only CDI information. The flight crew complained of the additional workload necessary to accurately overfly the VOR and monitor the DME along with the along-track and crosstrack information (see figure 7).

CONCLUSIONS

1. Present state-of-the-art receivers do not meet the Minimum Operational Performance Standards (MOPS) minimum criteria for proper cycle acquisition or time to acquire.

2. The probability to acquire on the proper cycle increases as field strength is increased and noise is decreased, and when the geometric dilution of precision (GDOP) is low.

3. Manufacturers feel the next generation receivers can be designed to acquire on the proper cycle nearly 100 percent of the time under certain signal conditions.

4. A cycle slip can be easily determined when and if the error causes a parallel offset. Crosstrack error or along-track error greater than 0.5 nautical mile (nmi) directly over a ground check point appear to be adequate for the pilot to determine if a cycle slip has occurred. (In the case where the crosstrack error is minimal but the along-track error is questionable, the pilot could not determine, with assurance, if the Loran was accurate enough to continue an approach).

5. A very high frequency omnidirectional (VOR) in the vicinity of the arrival airport can be used as an integrity check point if the Loran C derived distance measuring equipment (DME) to the waypoint of the station and Loran C derived course deviation indicator (CDI) are monitored. The pilot must fly a VOR radial to the station with precision. Preferably, visibility would be such that a visual siting of the station is possible. It is recommended that an altitude no greater than 2000 feet be used for the overflight. Over the station the pilot will note a flag appearance, a full scale needle deflection, and a to/from reversal. Again, it must be stressed that accuracy in overflying the VOR is most important.

6. The subject pilots commented that they would not choose to use either an nondirectional beacon (NDB) or marker beacon as an integrity check point. It was their impression that an NDB is not accurate enough.

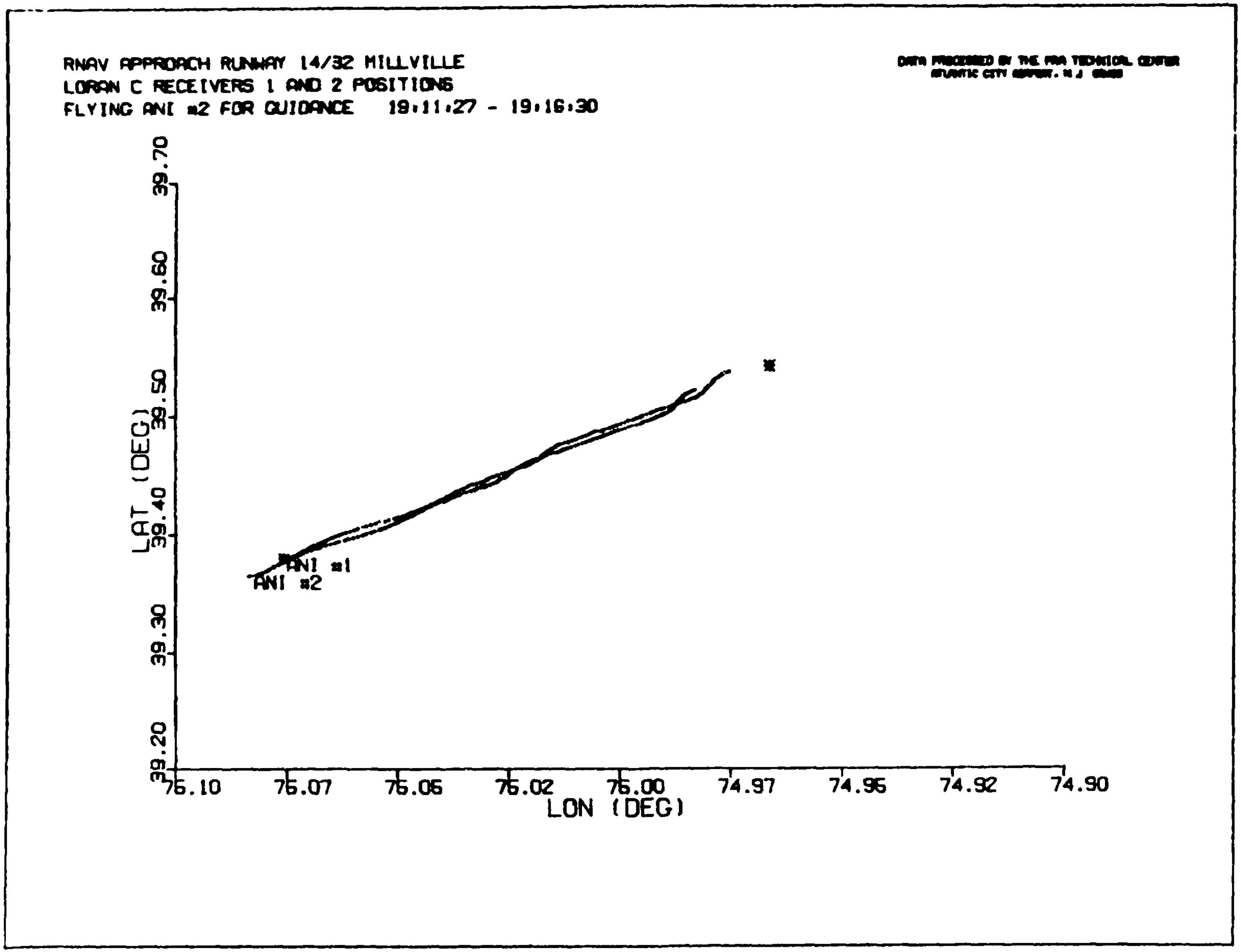

FIGURE 5. APPROACHES, MILLVILLE AIRPORT

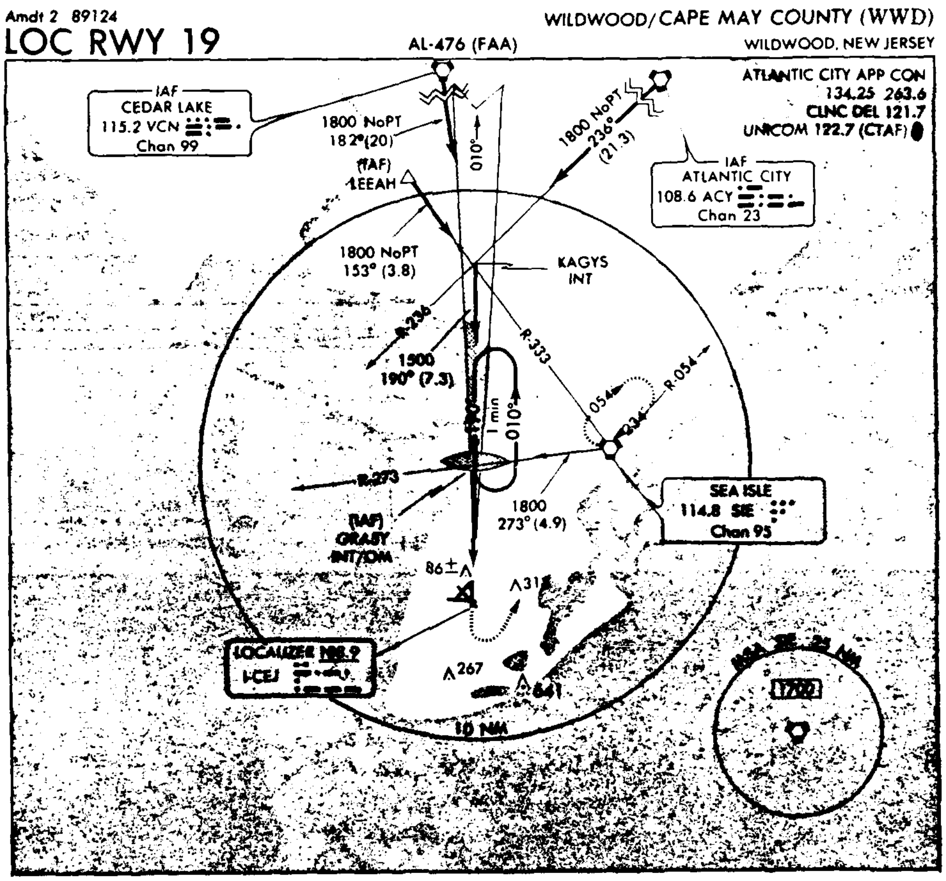

FIGURE 6. WILDWOOD/CAPE MAY AIRPORT APPROACH PLATE

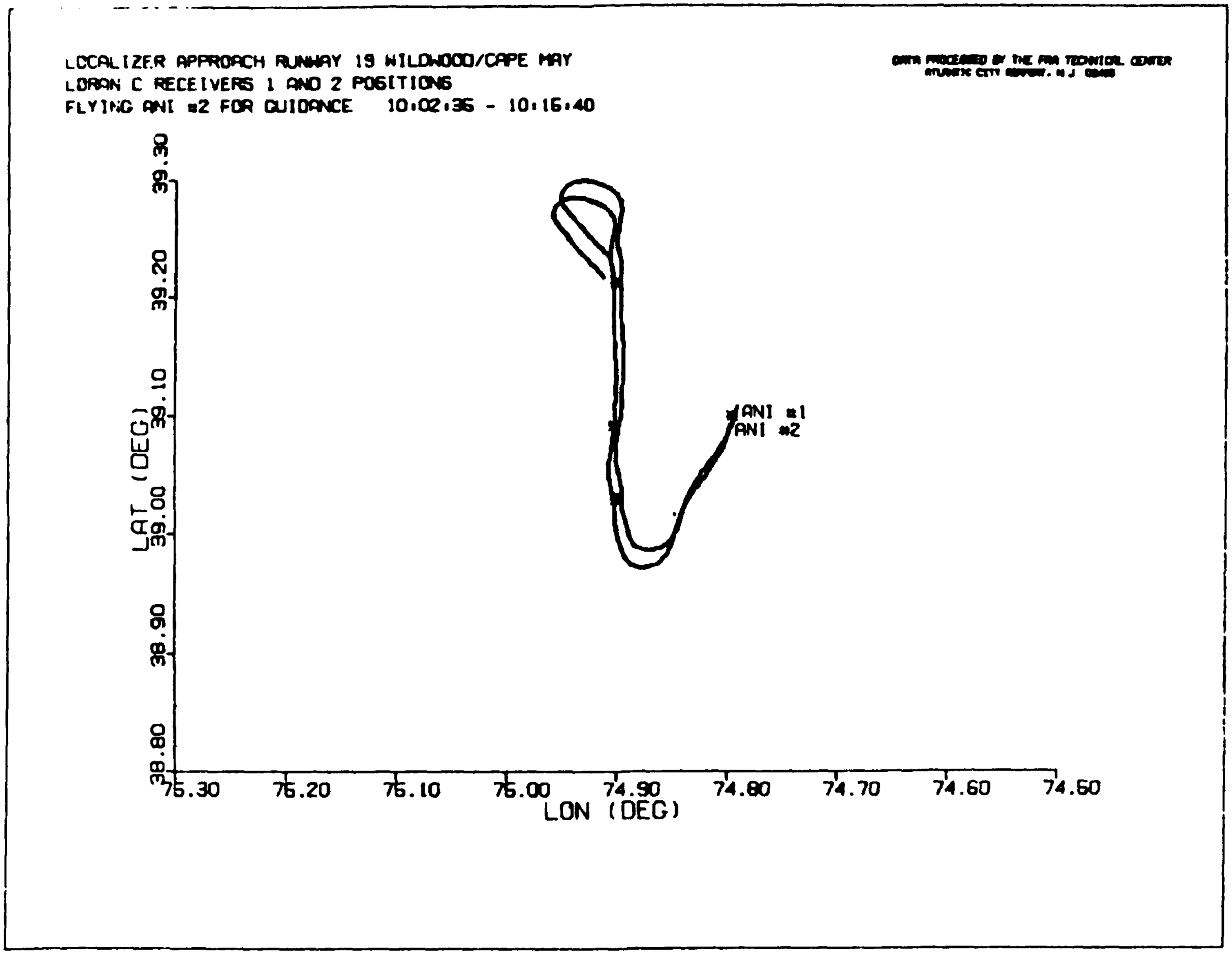

FIGURE 7. APPROACHES, WILDWOOD/CAPE MAY AIRPORT

7. A marker beacon could be used as an integrity check point in an emergency. It was the pilot's opinion that the marker beacon is located too close to the missed approach point to make a decision to abort or continue with the approach.

8. The issues of cycle slips and probability and confidence levels were readdressed by the Radio Technical Commission for Aeronautics (RTCA) committee and Federal Aviation Administration (FAA) personnel. The MOPS was changed to require a higher confidence level in testing Loran C receivers for cycle slips as a result of the findings in this report.

RECOMMENDATIONS

1. The criteria for establishing a Loran C nonprecision approach needs to be reviewed. Possible restrictions until manufacturers have demonstrated that their receivers meet the new integrity requirements in the Minimum Operational Performance Standards (MOPS) might be:

a. Flights must not go out of the chain or triad from which departure was made.

b. Field strength, noise, and envelope-to-cycle discrepancy (ECD) readings must be within some bounds in an area (i.e., field strength > 50 dB/μV/m, noise > 42 dB/μV/m, ECD between +3.0 and -2.4 microseconds).

c. A ground check point must be verified on the aircraft Loran receiver at the departure airport.

2. Overfly a very high frequency omnidirectional (VOR) in the vicinity of the arrival airport at an altitude low enough for visual siting, or VOR to/from flag indicates station passage while:

a. Monitoring Loran distance to waypoint and crosstrack error.

b. Monitoring the VOR bearing while flying to the station.

APPENDIX A

LORAN C SIMULATOR

The Advanced Navigation Incorporated (ANI) 2500 Loran C signal generator is a state-of-the-art test device that provides a stable reference based Loran C signal for a wide variety of static and dynamic test conditions. Each setup allows the selection of master and secondaries with individually set signal levels, noise levels, and envelope-to-cycle discrepancy (ECD) bias.

The Loran C signal generator consists of:

Description	Quantity
Loran C Generator - ANI Model 2500	1
Consisting of:	
Rockland Synthesizer model/5110-06 (2 megahertz)	1
Rockland Synthesizer model/5110-06-13 (3 megahertz)	1
Model 2044 Loran C Simulator	1
IBM Cathode Ray Tube (CRT)	1
IBM Personal Computer	1
Printer	1
Joy Stick	1

The Loran C ANI model 2500 signal generator system consists of two major subassemblies: a Loran C simulator unit and the IBM computer. Both units have monochrome displays and are interfaced by an RS-232 data bus.

The model 2044 Loran C simulator can simulate four chains with up to six secondary stations per chain along with ground wave and skywave component signals.

The Loran C signal structure is in conformance with the United States Coast Guard (USCG) publication "Specifications of the Transmitted Loran C Signal," COMDTINST M165624, July 1981. Individual adjustment is provided for station field strength, signal-to-noise ratio (SNR), and ECD. Continuous wave interference (CWI) is provided by two Rockland synthesizers operable over a range of 0 to 3 megahertz. Gaussian/atmospheric noise simulation is internally provided.

APPENDIX B

LORAN C IMPLEMENTATION QUESTIONNAIRE

LORAN C IMPLEMENTATION QUESTIONNAIRE

OBJECTIVE

The objective of this questionnaire is to solicit an input from receiver manufacturers to determine, in their opinion, if an operational integrity check is necessary before beginning a Loran C nonprecision approach.

BACKGROUND

The Federal Aviation Administration (FAA) has made a commitment to implement Loran C as an interim supplemental air navigation system. Once implemented, Loran C will be approved as a supplemental navigation system that can be used in controlled airspace of the National Airspace System (NAS) until at least the year 2003.

Loran C expansion will be supported by installing four Loran C transmitters to fill the mid-continent gap. Loran C nonprecision approaches will be supported by installing 102 monitors to provide an integrity check of the local Loran C signal in space and to provide local area bias corrections on a routine basis for the airborne receivers.

Loran C Minimum Operational Performance Standards (MOPS) have been developed through a joint effort of users, manufacturers, the FAA, and the Radio Technical Commission for Aeronautics (RTCA). The intent of the MOPS committee was to agree on a set of standards that all participants could live with and not compromise safety issues.

The safety issue was addressed in the MOPS by requiring the receivers to detect blink within 10 seconds and loss of signal within 15 seconds, down to a signal-to-noise ratio (SNR) of -6 decibels (dB) in the approach mode. The blink and loss of signal detection criteria were increased to 60 and 30 seconds, respectively, down to -10 dB SNR in the en route and terminal mode. At present, the United States Coast Guard (USCG) detects out of tolerance parameters and manually asserts blink. The USCG is considering automatically asserting aviation blink by shutting down the affected transmitter. This may require the FAA to specify in the technical standard order (TSO) that Loran C receivers meet a 10-second loss of signal detection interval for approaches.

The FAA has addressed the safety issue by initially restricting approaches in the limited implementation nonprecision approach program to geographical areas meeting good signal in space criteria, i.e., SNR shall be equal to or greater than 0 dB, envelope-to-cycle discrepancy (ECD) shall not exceed ± 2.4 microseconds, and geometric dilution of precision (GDOP) shall not exceed 3000 feet/microsecond. The approaches were also overlaid over another navigation aid (NAVAID) approach and a copilot was required to monitor the Loran approach with respect to the other NAVAID. These criteria could be relaxed if experience so indicates.

There is a concern over the ability of a Loran C receiver to reliably acquire and track the Loran C signal on the proper cycle. If Loran C is to gain wide acceptance and approval in the NAS, this issue must be resolved in the receiver design and by limiting operation to areas where wrong cycle acquisition is improbable. The MOPS addressed this issue by requiring receivers to detect or correct a cycle slip with 90 percent probability within 10 minutes in the en route and terminal mode, and within 3 minutes in the approach mode. The MOPS did not specify the probability associated with the approach mode, however, the test section of the MOPS requires the receiver under test to detect a cycle slip in 20 out of 20 test cycles. In addition, the MOPS requires the receivers to properly acquire and track with an ECD of 0 to -2.4 microseconds at SNR's from -6 to -16 dB, and ECD's of -2.4 to +3.0 microseconds at SNR's above -6 dB.

It has been suggested that an inflight operational integrity check (OIC) before beginning an approach is a necessary requirement to insure the receiver is tracking on the proper cycle. This could be accomplished by overflying a very high frequency omnidirectional range (VOR) or nondirectional beacon (NDB), or comparing position with another NAVAID. The addition of an OIC to a Loran C nonprecision approach procedure is undesirable because it complicates the procedure and adds another task for the pilot when he is entering a high work load phase. In addition, the advantage to fly point to point with Loran C may be severely compromised in areas where it is not possible or convenient to cross-check against another NAVAID. Mandating an OIC for every approach could seriously affect widespread acceptance and approval of Loran C in the NAS for nonprecision approach use.

An alternative to an OIC is to provide a ground check point (GCP) at an airport and require the pilot to compare his Loran C system against the coordinates of the GCP. Additional receiver software would be required to insure the receiver did not experience a cycle slip after completing a GCP validation. The minimum Loran C GDOP that users can experience is approximately 480 feet/microsecond. Hence, the minimum error for wrong cycle acquisition or track would never be less than 4800 feet. As GDOP increases, the position error caused by a cycle slip increases. This error could easily be detected at a GCP. The Loran receiver would require software to insure the position coordinates never change suddenly in flight to a value greater than or equal to a cycle slip, even when acquiring new stations. An OIC would be required only after inflight receiver initialization or when a new Loran C chain is selected.

QUESTIONS

1. Is it possible to design a receiver that will acquire and track on the proper cycle with nearly 100 percent probability?

2. If the answer to question 1 is yes, is it economically feasible to manufacture a receiver that will nearly always acquire and track on the proper cycle?

3. In your opinion, have you resolved the cycle slip issue with proprietary software or hardware?

4. If operation is restricted to geographical areas with good signal in space coverage, i.e., SNR and ECD above some minimum value, to what probability can you guarantee proper cycle acquisition and track? Specify the SNR, ECD, and other criteria to meet that probability.

5. What improvements, if any, would you recommend to the MOPS or a TSO to increase confidence in proper cycle acquisition of track?

6. What undetectable receiver failure modes, if any, could cause wrong cycle acquisition or detection?

7. In your opinion is an OIC necessary?

8. Can a GCP be used in place of an OIC?

9. Do you have any other comments or suggestions to resolve the cycle slip issue?

APPENDIX C

REPLIES TO QUESTIONNAIRE

Note: Actual names of manufacturers and model numbers of the receivers have been omitted and replaced with Brand A, B, or C and Model X, Y, or Z.

REPLIES FROM MANUFACTURER "A"

Thank you for the opportunity to provide our input on the subject of using Loran for nonprecision approach procedures. We have indexed our response per your questionnaire.

(1) The key word in your question is nearly. Brand A receivers acquire and track the correct cycle to -10 dB SNR at 95% probability and to approximately 97% at -6 dB. Improvements over this can be obtained with multiple line-of-position (LOP) solutions and we have, therefore, designed our airborne receivers to track up to ten staions. To answer your question, a number of 99.5% is attainable through various techniques but 100% will never be attainable because of special conditions and anomalies.

(2) The receivers described in (1) are not much further advanced than current models and next generation receivers will approach 100% reliability without significant cost increase.

(3) We have allowed for resolution of cycle selection by designing our airborne receivers to track up to ten stations. We have not yet completed software to take advantage of these stations in solving cycle slip problems.

(4) The limits for near 100% cycle selection would require:

- Signal-to-Noise Ratio -10 dB or better
- ECD ± 3 microseconds
- At least three secondaries or more than one chain

(5) Based on above answers, the MOPS or TSO should at least acknowledge the use of two chains to get maximum information and redundancy in resolving the cycle slip problem.

(6) Simple failures of any circuits will cause the set to malfunction in a way that will be obvious. However, if the envelope detection circuit or filters are slightly detuned, an ECD can be introduced by the set itself causing cycle errors.

(7) Inflight Operational Integrity Checks (OIC) must be used to check cycle selection on the rare occasions when a set must be reinitiated in flight unless other improvements are made, as above, to guarantee cycle selection. It is also worth noting that a two chain set can change chains without losing the correct cycle.

(8) Software is currently in place in Brand A sets to lock in the correct cycle and prevent change except in the case of loss of signal. OIC and GCP (Ground Check Point) are good navigation practices but should not be required if cycle selection improvements are made. Formal Ground Check Points are not really required as position should be known accurately enough at an airport to verify cycle acquisition (4800+ ft).

(9) Use multiple chains/stations to get maximum information and determine the correct cycle.

REPLIES FROM MANUFACTURER "B"

Here is a list of answers to the specific questions you posed with the corresponding numbers.

1. Yes - IF:

2. If a range limitation of 600 nautical miles is observed, then a receiver should acquire and track the proper cycle with nearly 100 percent probability. The only circumstance that would cause a cycle slip would be a period of p-static in which a severe maneuver was involved, followed by recovery of signals. This could conceivably cause a signal to track on the wrong cycle. If the receiver is designed to drop back to cycle acquisition mode after 30 seconds of SNR less than -25 dB, then this will never happen.

3. Within the limits specified above, the Brand B receivers acquire the proper cycle.

4. With SNR better than -10 dB (atmospheric) and ECD better than ± 2.5, then cycle slip should be, for all practical purposes, nonexistent.

5. The new RTCA DO-194 conditions should assure proper cycle acquisition at all times within the constraints stated above.

6. Detuning the r-f circuits or poorly located notch filters could distort the pulse to change the ECD values and cause cycle slip. Pulse distortion can occur in certain mountainous areas, but these can be determined in surveying for approach certification.

7. I do not think an OIC is necessary.

8. A GCP requires that the pilot see the ground, in which case he may not need the Loran for approach.

9. I do not believe that cycle slips are a major problem in most areas.

REPLIES FROM MANUFACTURER "C"

June 15, 1987

These comments are made in regards to the "Loran C Implementation Questionnaire" enclosed with the FAA letter dated Dec. 3, 1986.

Brand C has done extensive signal acquisition testing under different signal input conditions. We understand FAA's concern about only requiring 10 out of 10 correct signal acquisitions. By statistics, this provides a low confidence level of probability of accuracy.

Following are Brand C's response to the FAA questionnaire:

FAA Question:

1. Is it possible to design a receiver that will acquire and track on the proper cycle with nearly 100% probability?

Brand C Response:

It is possible to manufacture a receiver that will acquire 1000/1000. This implies by statistical analysis a 60% confidence to have a 99.9% proper cycle selection. However, this testing would be conducted under a specific set of test conditions stated below.

FAA Question:

2. If the answer to question 1 is yes, is it economically feasible to manufacture a receiver that will nearly always acquire and track on the proper cycle?

Brand C Response:

Brand C has thousands of the Model X Loran series receivers in service. These receivers currently may or may not correctly acquire 1000/1000 times. We feel that it would be technically and economically feasible to upgrade the existing Brand C Model X series units in service to meet this specification.

FAA Question:

3. In your opinion, have you resolved the cycle slip issue with proprietary software or hardware?

Brand C Response:

Yes, we feel that we have resolved the cycle slip issue with our proprietary software and hardware.

FAA Question:

4. If operation is restricted to geographical areas with good signal in space coverage, i.e., SNR and ECD above some minimum value, to what probability can you guarantee proper cycle acquisition and track? Specify the SNR, ECD and other criteria to meet that probability.

Brand C Response:

Brand C could achieve 1000 out of 1000 under any one of the following set of signal conditions:

Signal level;	50 dB microvolts per meter
SNR;	-2 dB (atmospheric)
ECD range;	-2.4 to +2.4 microseconds

Signal level;	40 dB microvolts per meter
SNR;	0 dB (atmospheric)
ECD range;	-2.4 to +2.4 microseconds

Signal level;	40 dB microvolts per meter
SNR;	-6 dB (atmospheric)
ECD range;	-3.5 to +1.0 microseconds

FAA Question:

5. What improvements, if any, would you recommend to the MOPS or a TSO to increase confidence in proper cycle acquisition or track?

Brand C Response:

It is Brand C's opinion that the weakest point in the MOPS testing is the Antenna Simulator which is a device that replaces the actual antenna to facilitate laboratory testing. The MOPS did not provide the means or address the calibration of this device. Since all tests are conducted using this device, the results of all of the MOPS testing are in question.

See Brand C's comments on DO-194 for additional information.

FAA Question:

6. What undetectable receiver failure modes, if any, could cause wrong cycle acquisition or detection?

Brand C Response:

The safety analysis conducted on the Model Y as part of the STC program demonstrated that the probability of undetectable receiver failure meets the same requirements for essential category as other navigation equipment. This is based on the assumption that the Loran accuracy is checked for reasonableness prior to use as a means of navigation.

We see future designs that will test and monitor all hardware circuits, including the receiver tuned circuits, to verify proper operation during and after the acquisition cycle selection process. This will result in all receiver failure modes being detectable.

FAA Question:

7. In your opinion is an OIC (operational integrity check) necessary?

Brand C Response:

An OIC is not necessary. All receiver testing conducted by Brand C has demonstrated that the potential failure mode is associated with proper cycle selection during acquisition. Under no circumstances have we experienced failure of cycle slip after proper acquisition has been achieved. As with all navigation equipment, reasonableness checks must be conducted by the pilot prior to use. For the Loran receiver, we consider proper cycle selection during acquisition the issue and not cycle slip. We suggest in place of an OIC, the same method used for other navigation systems, that is, a reasonableness check prior to use. We consider that a reasonableness check verifying that the position error is less than 3 nmi is adequate to ensure proper cycle selection. This reasonableness check verifies proper operation the same as checking the VOR receiver or other navigation receivers prior to flight. Certification testing and safety analysis are necessary and sufficient to ensure system integrity.

FAA Question:

8. Can GCP (ground check point) be used in place of an OIC?

Brand C Response:

A GCP is not requires. Use the reasonableness check method.

FAA Question:

9. Do you have any other comments or suggestions to resolve the cycle slip issue?

Brand C Response:

Brand C is currently working on different techniques to drastically improve the integrity of the cycle selection. However, this data is proprietary and cannot be discussed at present.

DO-194 Comments

Brand C has reviewed RTCA DO-194 "Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using Loran-C Inputs" November 17, 1986, and are making the following comments.

Our comments are based on the adequate field performance of the Brand C Model X series Loran (including the Model Y and the Model Z) and the extensive laboratory testing we conducted on the Model X series Loran. In addition to testing our own equipment, we have conducted performance tests on our competitors' Loran receivers for comparision to our receiver and to determine performance limitations.

Signal-to-Noise Ratios

The signal-to-noise ratios of -16 dB microvolts per meter atmospheric should be replaced with -10 dB microvolts per meter atmospheric. Current receiver designs marginally meet this specification, but in the real world, adequately perform.

ECD Values

The ECD values are not consistent with real world conditions. Low level signals will be a long distance from the transmitter and that over this long distance, the propagation delay of the envelope vs. the rf results in a negative ECD at the receiver. We make the following suggestions to table 2-6:

	Sm	Sx	Sy	Sn	ECDm	ECDx	ECDy
Test Case	1						
was	110	30	30	30	+3	+2.4	-2.4
suggest	110	30	30	30	+3	0	-2.4
Test Case	3						
was	40	40	40	46	0	-2.4	+2.4
suggest	40	40	40	46	0	-2.4	0

Skywave ECD

Test case nos. 5 through 18 in table 2-6 are testing for skywave interference. The skywave data specified is the T (skywave delay with respect to groundwave) and S (signal strength of skywave in dB microvolts per meter), whereas the skywave ECD is not specified. We assume that the skywave delay is from the ground wave cycle zero crossing to the skywave cycle zero crossing, not to the ground wave envelope to the skywave envelope, and assume that the skywave ECD is equal to 0.

These items should be specified since changing these assumptions could change the test results entirely.

There is also a typographical error in the definitions under the table 2-6. The definition "* Skywave and ECD are..." should be "* Skywave and signal level are...".

Interference Noise Test

Paragraph 2.2.3.3 states;

> "The equipment shall be able to properly acquire and track Loran C signals in the presence of non-synchronous continuous near-band interference with -20 dB signal-to-interference ratios..."

Paragraph 2.5.1.d states;

> "The circuits of the equipment under test shall be aligned and adjusted in accordance with the manufacturer's recommended practices prior to the application of the specified tests."

The requirement paragraph gives a bandwidth to test within and table 2-6 gives six frequencies to test at. In order to pass this test defined in table 2-6 with a fixed-notch design, the equipment manufacturer must tune the notches to the frequencies indicated in table 2-6 (or have auto notches). Since these interference frequencies will change with time, this document is dated and the equipment manufacturer will have to tune the notches to pass the test, but not for the real world environment.

Either there should be a foot note added to table 2-6 to allow the equipment manufacturer to adjust the notch filters specifically for the specified frequencies when testing, or allow the manufacturer to choose the interference frequencies within a specified bandwidth.

Acquisition Under Combined Conditions

Paragraph 2.5.2.7 states;

> "... For test Nos. 5 through 23, acquisition on the proper cycle shall be achieved at least 9 out of 10 trials."

A 90% probability of obtaining the correct cycle selection is not acceptable. A better alternative would be to allow 10 out of 10 correct acquisitions within 600 seconds with a 90% probability.

Cycle Slip

Cycle slip tests are tested under several conditions including under skywave conditions.

Paragraph 2.5.2.12 states;

> "... 90% of the tests should result in an alarm or a correction of the error."

This statement should be removed requiring 10 out of 10 trials correct.

Added Acquisition Test

Since some receiver designs rely on past history of operation, (ie. where the receiver was turned off) to acquire the signal, some test should be devised to properly test the Loran receivers to test for a "cold" start. This "cold" start would not use the previous position data to get started (ie. the unit turned off at Salem and not turned on until it is in Seattle). The allowable acquisition time for this test could be longer than the normal 450 seconds.

Antenna Simulator

Paragraph 2.5.2.c(1) specifies how the antenna may be replaced by the equivalent series impedance. What method manufacturers use to determine the equivalent series impedance is not defined. The capacitance of the antenna can be measured, but it is difficult to determine the distribution of the capacitance of antenna to ground vs. the capacitance antenna to the air.

Since all of the minimum performance tests defined in DO-194 are dependant on this "antenna simulator," the manufacturer must have a way of calibrating the "antenna simulator." Brand C has developed one method using a calibrated electric field cage. This cage produces a calibrated signal to the receiving antenna. By comparing the actual antenna to the antenna simulator, the antenna simulator can then be calibrated.

All minimum performance tests in DO-194 suggest testing with the antenna simulator. The actual antenna performance is also a very critical part of the system and there are no guidelines or procedures for testing the minimum performance of the antenna system. Any antennas being qualified for Loran TSO should be required to be tested under calibrated laboratory conditions. Uncalibrated probe techniques may provide false signal levels and ECD inputs to the antenna. The RTCA DO-194 should address how to properly test Loran antennas. Brand C's calibrated electric field cage provides one method of testing antennas. Other methods may exist.

Dynamic Tracking

Paragraph 2.5.2.8 failed to give signal levels for the Master and the secondaries, 40 dB microvolts per meter is probably an adequate level. The noise level will have to also be adjusted.